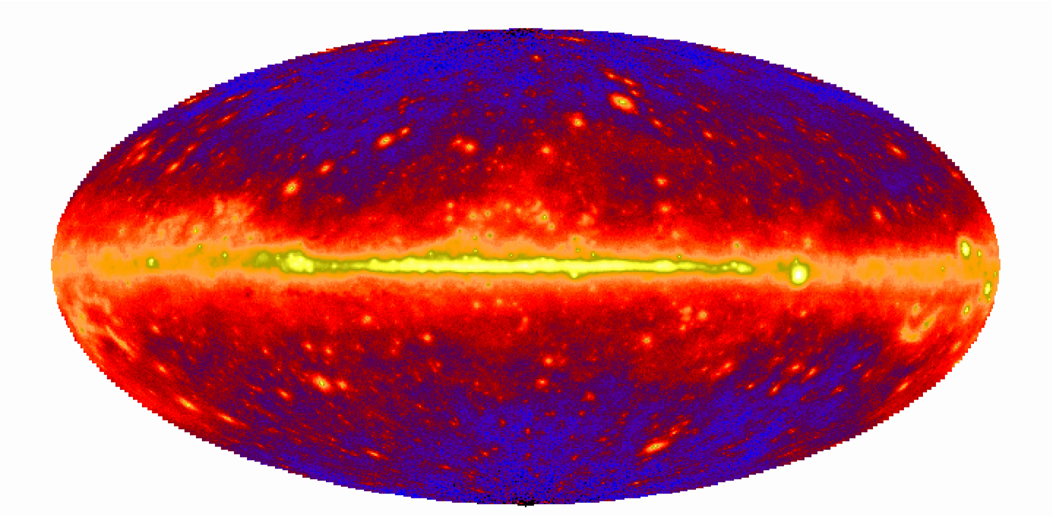
Table of Contents

The Gamma-ray Large Area Space Telescope (GLAST) begins a new epoch in space-based physics investigation. Using the most powerful particle accelerators in the Universe as cosmic laboratories, GLAST will explore the link between gravitation and quantum physics in the extreme environments of supermassive black holes, neutron stars, and gamma-ray bursts. On cosmological scales, GLAST will explore the era of star formation in the Universe, the physics of dark matter, and the creation and evolution of galaxies.

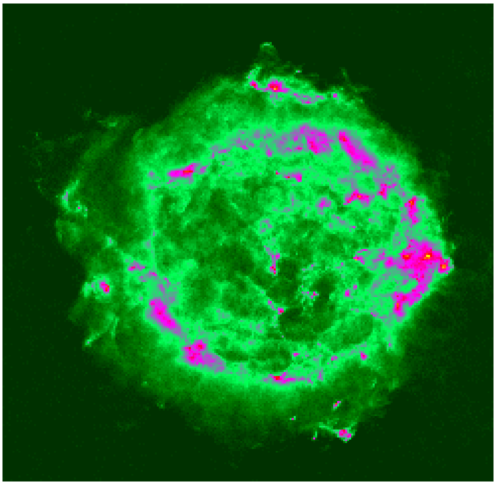
GLAST will be sensitive to celestial gamma rays in the 10 MeV to 300 GeV portion of the electromagnetic spectrum. Gamma rays are the most penetrating of electromagnetic radiation, and afford a direct view of the high-energy processes acting in the innermost regions of cosmic accelerator engines. GLAST will image the gamma-ray sky with unprecedented precision using state-of-the-art tracking technology developed in particle physics laboratories. GLAST's design achieves a large field of view — practically the full unocculted sky — and a sensitivity sufficient



The simulated gamma-ray sky as might be seen by GLAST after one year of observations in all-sky survey mode. Cosmic rays interact with the interstellar gas in our Galaxy to produce the diffuse Galactic background. The point sources scattered across the sky at high Galactic latitude are blazars. A blazar is an active galactic nucleus that we view almost along the axis of one of the jets.

to detect thousands of active galactic nuclei per year. GLAST will precisely image hundreds of mysterious gamma-ray bursts, recently shown to be the most powerful and distant explosions in the Universe since the Big Bang itself. We are on the threshold of a new era; GLAST will be to gamma-ray astronomy what Galileo's telescope was to optical astronomy.

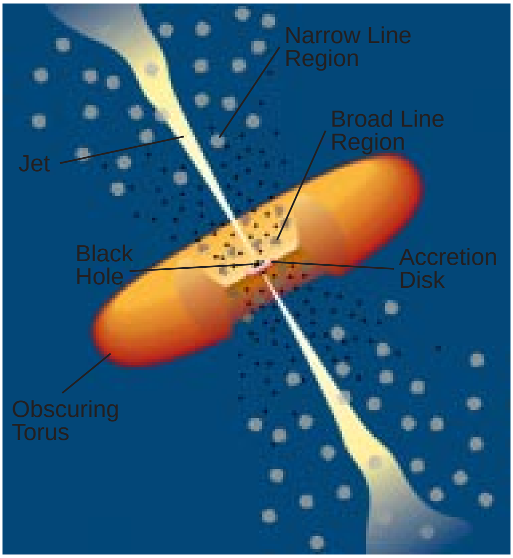
The last frontier of the very small is the very large. In attempts to realize Einstein's vision of a Unified Field Theory of the forces of nature, we have explored microphysics in Earth-based laboratories. Using our most powerful man-made particle accelerators, we have attained knowledge



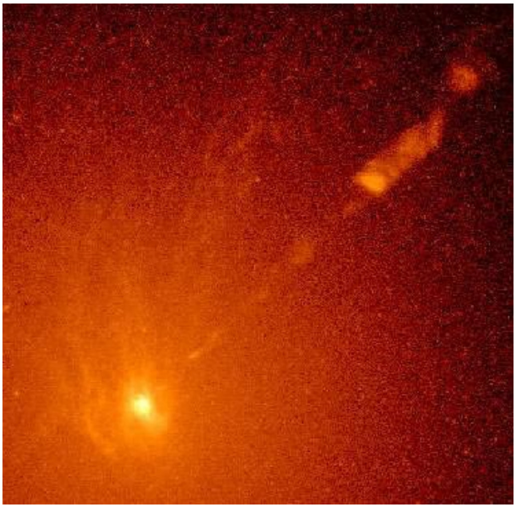
of the smallest scales and highest energies practical, where gluons hold together the quarks which make up the protons and neutrons of the ordinary matter we experience. Three of the four known forces in nature — electromagnetic, the weak force, and the strong nuclear force — are well understood. The signatures of unification between gravity and these three forces will be manifest at the ultimate energies, which are beyond the reach of Earth-based accelerators. The only approach available to grand unification of physics knowledge is to utilize the Universe's most extreme cosmic environments as our high-energy laboratories. GLAST initiates the space-based era of ultimate physical inquiry, uniting the fields of astrophysics and experimental particle physics.

Active Galactic Nuclei

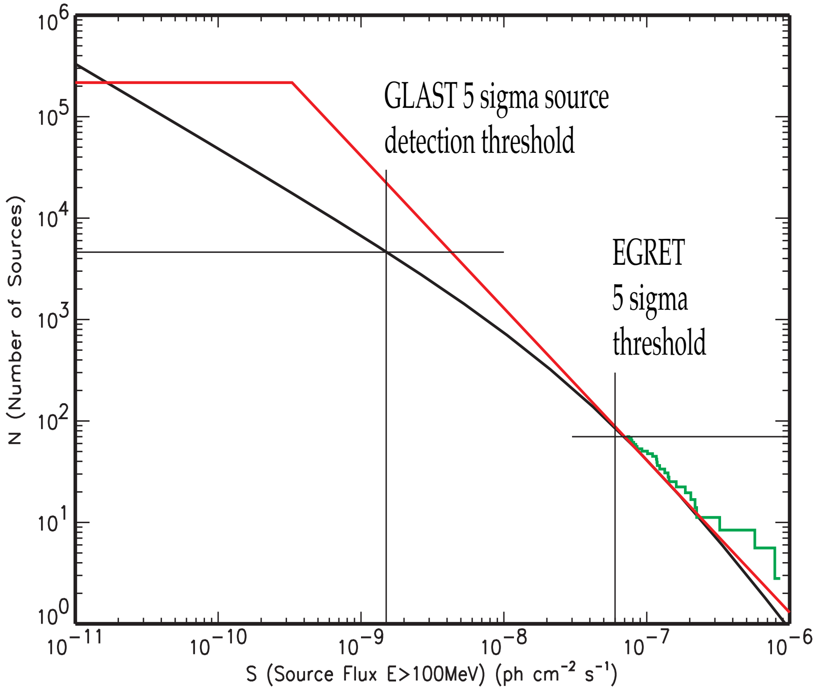
The largest identified class of high-energy gamma-ray sources is a type of Active Galactic Nuclei (AGN) called blazars. The Energetic Gamma Ray Experiment Telescope (EGRET) on board the Compton Gamma Ray Observatory detected more than 50 blazars; GLAST will see thousands. These large redshift extragalactic objects are incredibly powerful sources, each believed to contain a central rotating supermassive black hole with jets of relativistic particles emanating from near its poles. AGN are generally only detected as high-energy gamma-ray sources when one of the jets is directed towards the observer, a geometry for which the accretion torus surrounding the black hole does not obscure us from the black hole or the inner part of the jet. Even for this geometry, however, gamma rays are the only kind of electromagnetic radiation that can directly escape from the central region. Thus, GLAST observations of blazars will provide us with a unique opportunity to study what is happening on the doorsteps of billion-solar-mass black holes.



A schematic diagram for radio-loud AGN. A pair of relativistic jets emanate from near the poles of the central rotating supermassive black hole. High-energy gamma-ray emission is detected if we view the AGN almost along one of the jets.



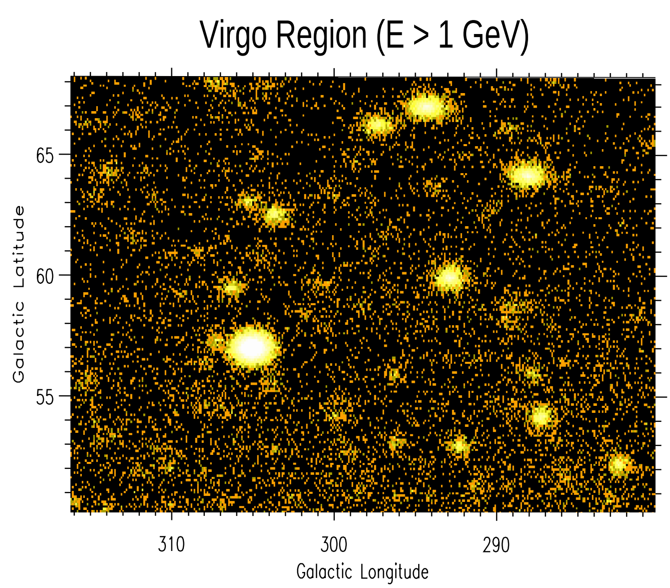
The nucleus and jet of the active galaxy M87.



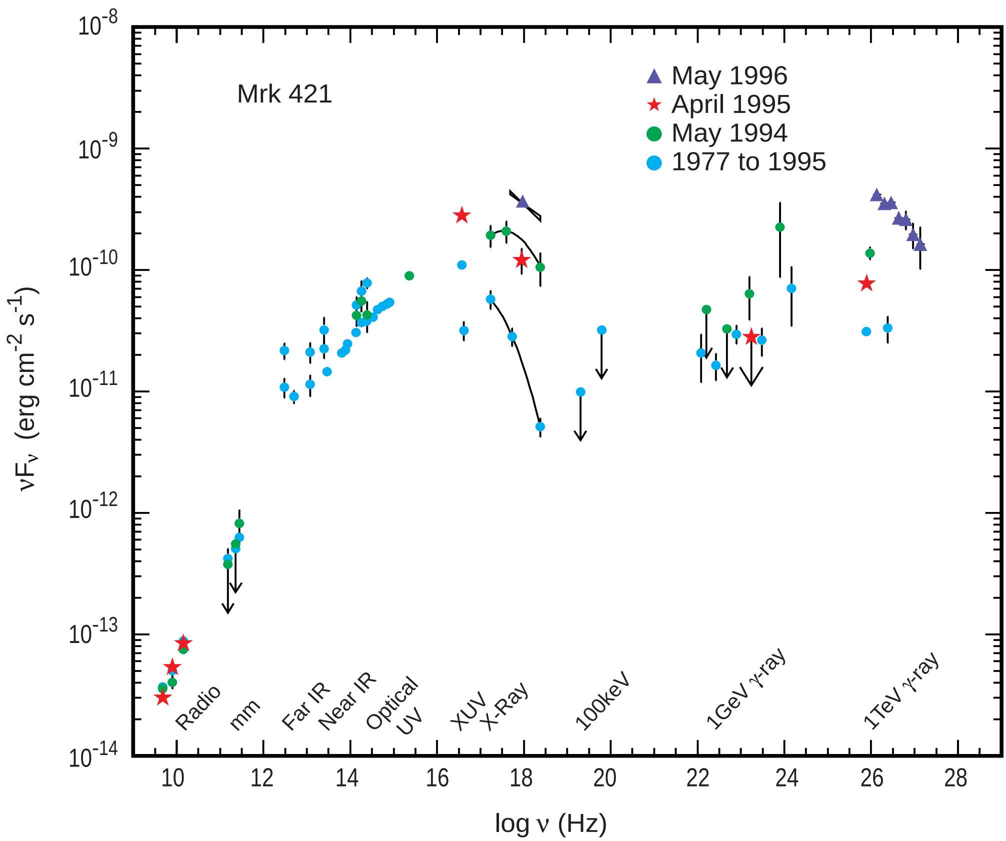
Left: Extrapolations of EGRET observations of blazars and the diffuse extragalactic background suggest that GLAST will detect thousands of AGN.

Below: A simulated view of what GLAST might see in the Virgo region above 1 GeV in a one-year all-sky survey. The field will contain many blazars.

GLAST studies of high-energy gamma-ray emission from blazars will help answer some of the most important questions we have regarding AGN: How do the jets form? How are the energetic particles accelerated? How are these particles collimated into such narrow cones? What sort of Lorentz factors are involved? What are the fundamental parameters governing the central engine?



Multiwavelength observations (radio, millimeter, infrared, optical, ultraviolet, X-ray and gamma-ray) are essential for understanding the nature of AGN. Emission in the GeV regime is especially important, since EGRET observations reveal that the amplitudes of AGN outbursts are often the largest at these energies. Thus, GLAST will provide a near real-time alert signal to observers at other wavelengths that an AGN outburst has begun.

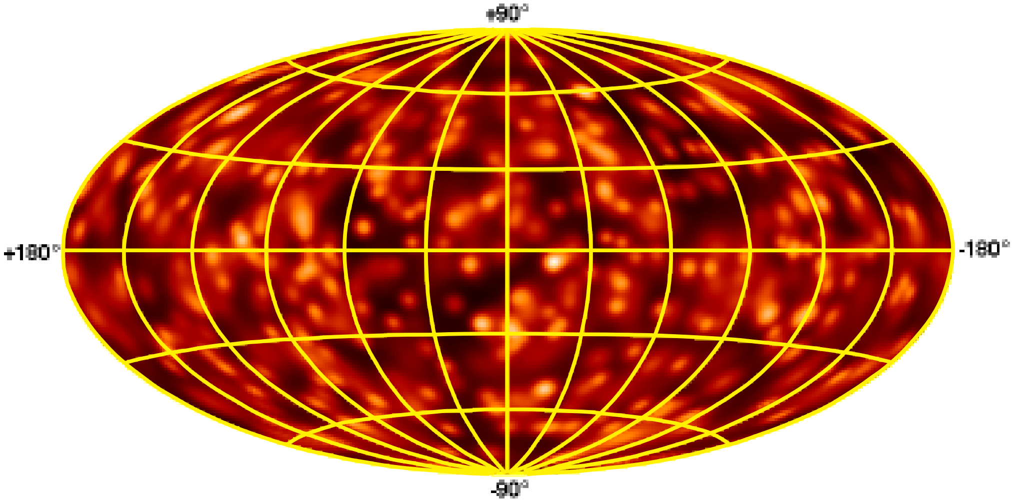


Multiwavelength observations of the blazar Markarian 421 indicate that much of its radiation is emitted at high energies, especially during flares. GLAST will bridge the gap that currently exists between EGRET and ground-based TeV observations where the second spectral peak, due to inverse Compton scattering, often occurs.

Gamma-Ray Bursts

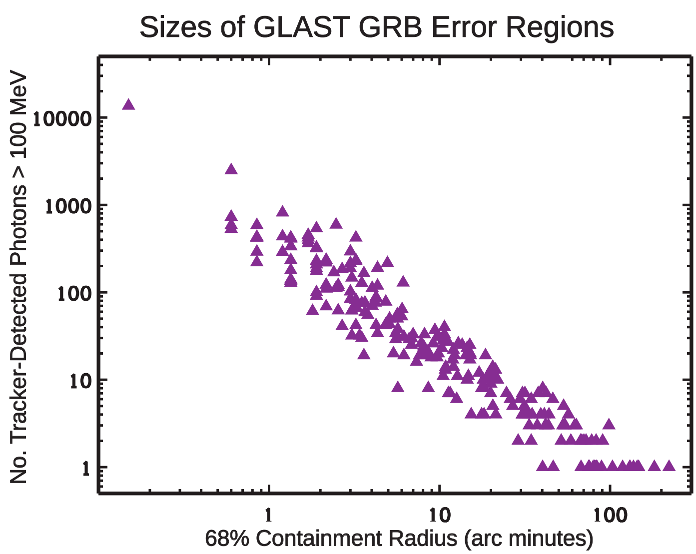
The origin of the incredible cosmic gamma-ray bursts (GRBs) is the longest enduring mystery in modern astrophysics. This phenomenon may be the result of a merger between a pair of neutron stars, a neutron star and a black hole, or a pair of black holes. The energy released during a GRB is comparable to the rest mass energy of the sun, and temporarily creates the most extreme physical conditions experienced in the Universe since the Big Bang itself.

The duration of a typical GRB is anywhere from 0.01 to 1000 seconds, during which time it will be the brightest source in the gamma-ray sky. The peak apparent fluxes of bright GRBs are a hundred to a thousand times larger than those of the AGN detected by EGRET. The dimmest GRBs are comparable with the Vela pulsar — the brightest steady gamma-ray source in the sky.



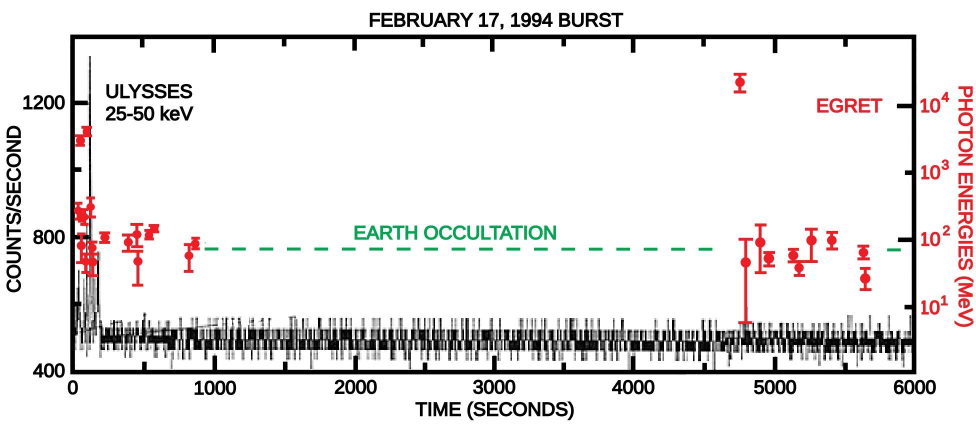
The positions on the sky of gamma-ray bursts in the BATSE 3B Catalog (BATSE is the Burst And Transient Source Experiment on board the Compton Gamma Ray Observatory). The fuzziness reflects the uncertainty in each BATSE position, which is typically several degrees.

On February 28, 1997 and again on May 8, 1997, the Italian-Dutch X-ray satellite, BeppoSAX, observed fading X-ray emission from GRBs for many hours after the gamma-ray emission had ceased. The GRB sources were localized with arc-minute accuracy, and faint (V > 20) optical transients were discovered in each case. The February 28 counterpart coincided with a faint extended object, which is consistent with a "dim blue galaxy." These galaxies were quite common when the Universe was half its current age. The optical spectrum of the May 8 counterpart revealed an absorption line system and an emission line all with redshift z=0.835. The fact that the emission line faded away suggests that this is the redshift of the GRB source. Consequently, GRB sources are now believed to lie at cosmological (gigaparsec) distances by virtually all astrophysicists.



GLAST's capability to localize GRB's to within a few arc minutes will enable follow-up observations at longer wavelengths for hundreds of GRBs each year.

Progress towards unravelling the GRB mystery is currently being made by virtue of multiwavelength detections and studies. However, understanding the physical nature of GRBs will take many more years of observation. GLAST should detect virtually all GRBs that occur in its field of view, and perhaps half of the 200 to 300 bursts per year detected by GLAST will be localized to better than a 10 arc-minute radius. GLAST's localization accuracy is comparable with BeppoSAX (5 arc minutes), but its GRB detection rate is much larger, by a factor of roughly 30. Only a fraction of GRBs appear to have optical counterparts, and therefore several years worth of GRB redshift determinations will be necessary to precisely calibrate the GRB distance scale, and help us understand the exotic physics that is taking place within and around GRB sources.

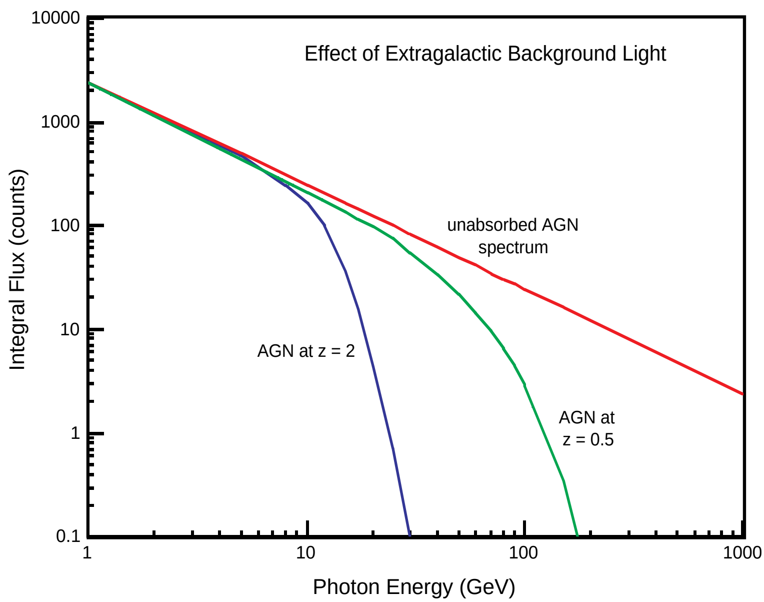


EGRET observed delayed GeV emission from a few GRBs, including the GRB of February 17, 1994, in which a 20 GeV photon arrived 80 minutes after the burst began. These delayed high-energy photons may be due to inverse Compton scattering of X-ray afterglow photons off ultrarelativistic electrons in the expanding fireball. GLAST will detect GeV photons from more than 100 GRBs each year, well characterizing the delayed GeV emission phenomenon.

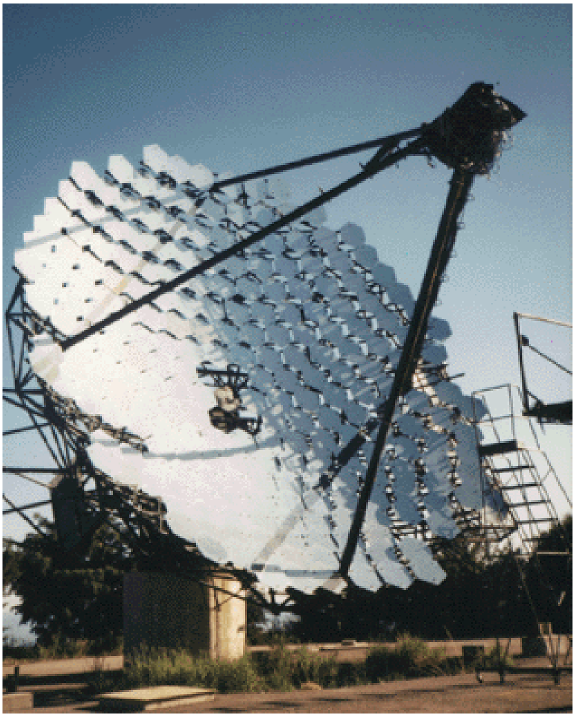
GLAST will provide high quality spectral data up to energies of 100 GeV for roughly two dozen GRBs per year. These spectra will place strong constraints on the photon production mechanisms and the physical conditions of the source region. For example, the escape of 100-GeV photons is very sensitive to the presence of lower energy photons, which induce pair production and thus attenuate the emission at high energies. Measurement of the high-energy cutoff in the spectrum of a GRB will constrain the Lorentz factor of the bulk relativistic motion in the source.

Cosmology

GLAST measurements of the spectral cutoffs of high redshift (up to z~4) AGN in the 10 to 100 GeV range will probe the Extragalactic Background Light (EBL) produced by galaxies undergoing starbursts during the epoch of star formation in galaxies. The absorption of high-energy gamma rays occurs over cosmological distances via interactions with the near-ultraviolet, optical and near-infrared photons that make up the EBL. Determination of the EBL can provide unique information regarding the formation of galaxies at early epochs, and will test models for structure formation in the Universe, such as those in which a neutrino mass of 5 to 10 eV plays an important role.



High-energy gamma rays emitted by distant AGN can interact with EBL photons before they can reach us. Shown above is how a power-law AGN spectrum would appear if observed at redshifts of z = 0.5 and 2 for a particular EBL model. GLAST observations of the high-energy spectra of a large sample of AGN at various redshifts will map out the EBL, and the luminosity function of the sources.



The Whipple Observatory 10-m detector. Ground-based gamma-ray telescopes, present and future, are an important complement to satellites operating at lower energies.

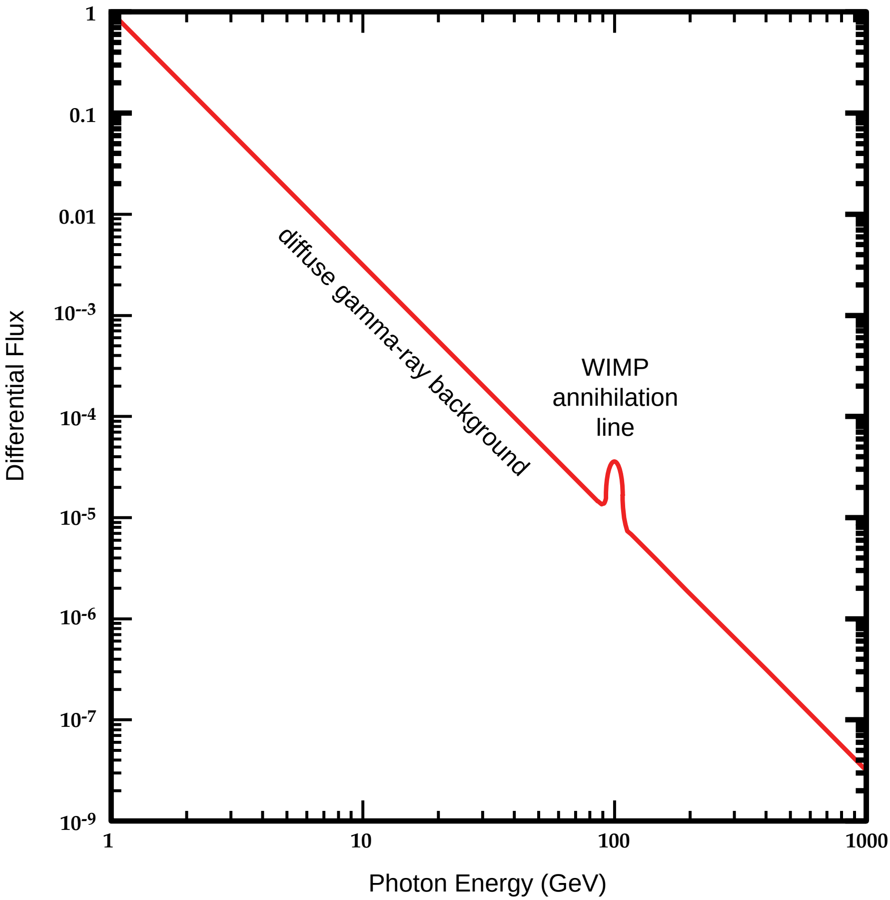
Since gamma-ray bursts (GRBs) likely come from sources at cosmological distances, GLAST measurements of the spectra of GRBs at various redshifts will also further the study of cosmic chemical evolution, assuming that host-galaxy counterparts can be identified from which to measure redshifts. The spectral coverage of GLAST also allows a connection to ground-based detectors that have already seen TeV emission from AGN, and may some day detect such emission from GRBs. The latter may become a reality with the help of real-time GRB localizations from GLAST.

Particle Astrophysics

GLAST will probe novel astrophysical phenomena which could arise as a result of new physics beyond our current standard model of particle interactions. It is well established that, like most spiral galaxies, our own Galaxy is immersed in a dark halo that outweighs the luminous component by perhaps an order of magnitude. The nature of this dark matter is one of the biggest mysteries in particle physics and cosmology.

One of the leading candidates for the dark matter is a stable weakly-interacting massive particle, or WIMP. For example, in supersymmetric extensions of the standard model, the particle could be a neutralino, which is a linear combination of the supersymmetric partners of the photon, Z^0 and Higgs bosons. In the most plausible models, the mass of the WIMP falls between 10 GeV and 300 GeV. If WIMPs exist in the Galactic halo, then they could annihilate and produce gamma rays with photon energies equal to the WIMP mass.

Huge amounts of dark matter in a cluster of galaxies can gravitationally lens a single background galaxy into several arc-shaped images.

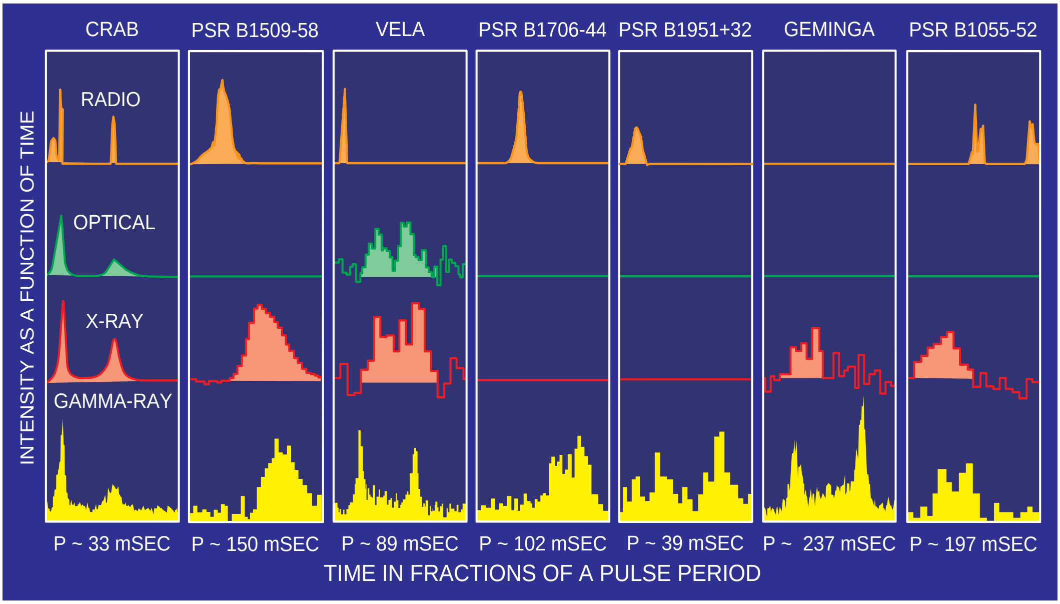


Simulation of a WIMP annihilation line superposed on the diffuse isotropic gamma-ray background.

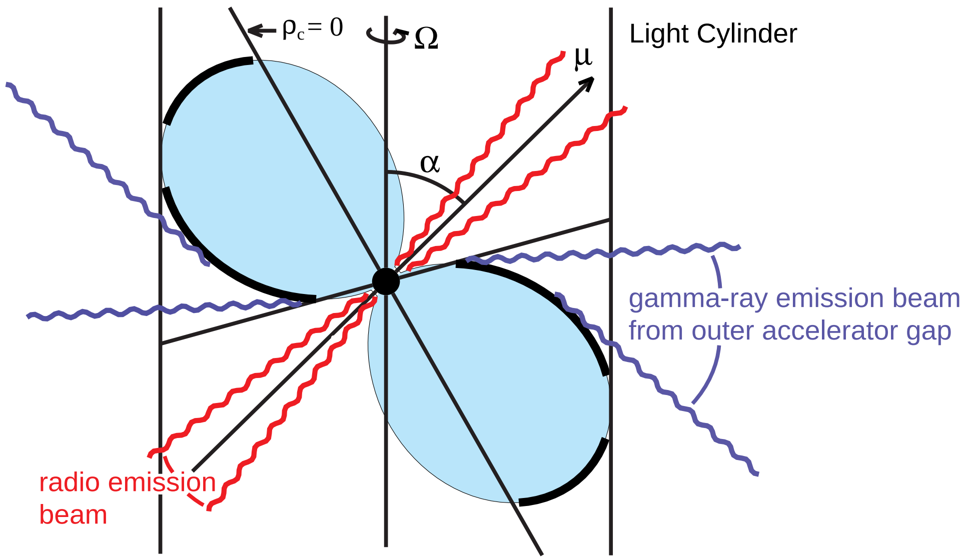
For example, the figure above shows how the annihilation line for a WIMP with a 100 GeV rest mass, smeared by a 10% instrumental energy resolution, might stand out from the smooth power-law spectrum of the diffuse isotropic extragalactic background. The latter is probably due to emission from a multitude of faint active galactic nuclei. A WIMP emission line is by no means guaranteed, even if WIMPs are the dark matter. However, if GLAST were to detect such a line, it would be a clear signature of WIMPs in the Galactic halo.

Gamma-Ray Pulsars

Rotation powered pulsars are central to high-energy astrophysics, with the Crab pulsar serving as the standard candle of X-ray and gamma-ray astronomy. Although radio pulses remain the most studied data from these rotating magnetized neutron stars, EGRET observations show that gamma-ray emissions in the MeV to multi-GeV band dominate the total radiation emitted from young pulsars. Moreover, as the neutron star spins, EGRET data show that variations in the GeV emission arise from the changing view into the pulsar magnetosphere. Consequently, high-energy gamma-ray observations can map the pulsar magnetosphere and provide unique information regarding the physics of pulsar emission.



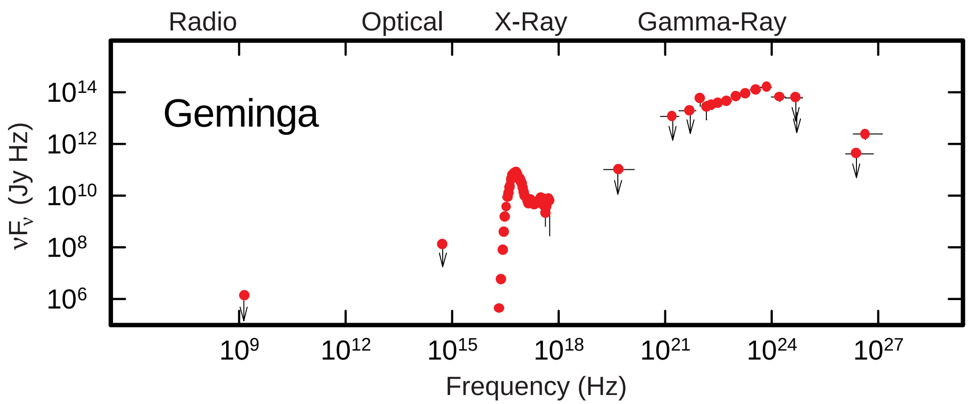
Multiwavelength light curves of the seven pulsars detected with EGRET. A flat line in the radio, optical or X-ray bands means that no such pulsation has been detected. GLAST should provide gamma-ray light curves for several dozen pulsars, which combined with the pulse shapes measured at other energies will severely constrain theoretical models for pulsar emission.



The outer-gap model for pulsar emission.

The prominence and rich temporal structure of pulsar gamma-ray emission offer the best hope of using high-energy observations to understand the physics of an astrophysical particle accelerator. The large effective area and broad energy sensitivity of GLAST are essential for providing the high quality pulse profiles and spectra needed to allow "reverse engineering" of the pulsar machine, which can accelerate charges to energies far beyond those attainable in terrestrial laboratories.

EGRET has detected pulsation from only a handful of objects, including Geminga, which is not seen in the radio. However, the discovery of numerous unidentified point sources in the Galaxy make it likely that many other pulsars await detection. Millisecond pulsars and pulsars in binaries may also be visible with GLAST, giving key insights into the physics of these exotic systems. Gamma ray pulsars provide an independent picture of the birth and evolution of neutron stars, and therefore a GLAST pulsar survey will open a new window on the Galactic neutron star population.



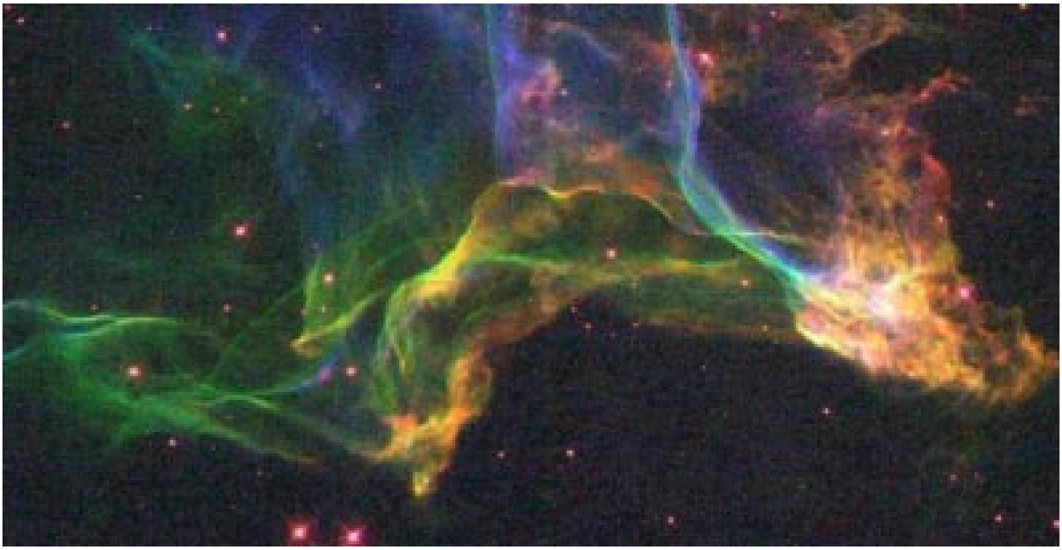
The energy output of the Geminga pulsar peaks in the gamma-ray region of the spectrum.

Acceleration of Cosmic Rays

The origin of the cosmic rays is one of the major outstanding questions of high-energy astrophysics. Most astronomers believe that cosmic rays are made from low-energy charged particles that are injected into interstellar space by flare stars or the winds of rapidly evolving massive stars. These particles are then accelerated by interactions with shocks from energetic supernova events. Less than 30% of the total power of Galactic supernovae is enough to produce all of the cosmic rays with energies up to roughly 1 TeV. (The cosmic rays observed to have energies of many TeV might be accelerated by the jets of active galactic nuclei.)

However, in spite of the popularity of this idea for the origin of the cosmic rays, the observational evidence needed to convincingly confirm this scenario has not been found. The interaction of cosmic rays with gas swept up by the supernova blast should also produce pions which decay into high-energy gamma-ray photons, but these have not been detected either.

Even though EGRET has detected gamma rays from six supernova remnants that contain pulsars, and has set upper limits on the emission from several plerion-type supernova remnants, none of these sites are suitable places to look for cosmic ray acceleration. Instead, the best locations are middle-aged (10^4 to 10^5 year-old) shell supernova remnants that do not contain pulsars. The shell indicates the extent of the shock front, which spreads out with time, and interacts with the local interstellar gas. Gamma-ray emission from the shock front is expected to remain almost constant at detectable levels during this time (roughly 10^{-7} photons cm^{-2} s^{-1} for a supernova remnant at a distance of 1 kpc). Many shell remnants are visible and resolvable in lower energy bands (e.g., radio, optical, X-ray), but none have yet been detected in high-energy gamma rays. A number of such shell remnants exist in the Galaxy, some with angular extents of up to three degrees, which makes them excellent candidates for GLAST observations. GLAST will be the first gamma-ray telescope with the ability to detect extended supernova sources and resolve them. Indeed, these non-pulsar-dominated shell supernova remnants, which hold the key to the cosmic-ray mystery, will be among the first extended gamma-ray objects ever imaged.

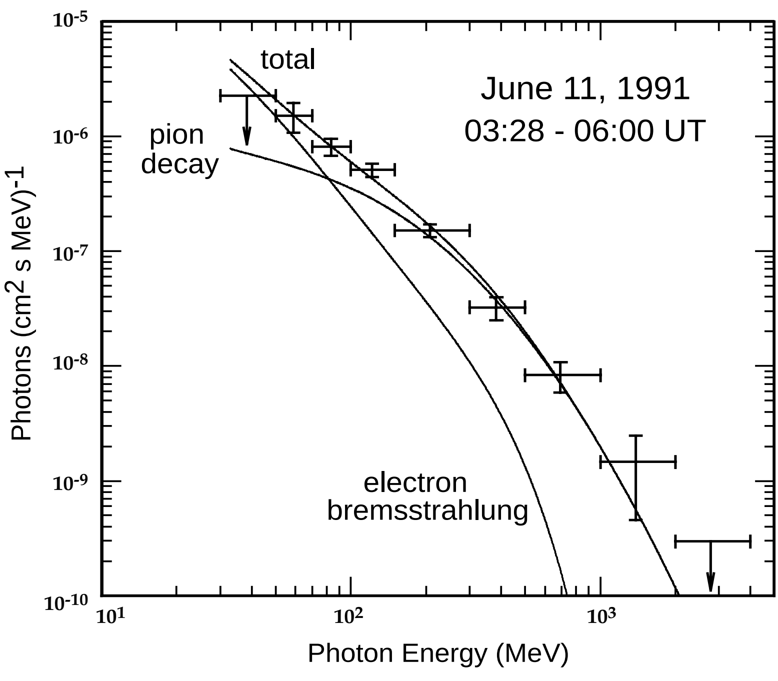


Part of the Cygnus Loop, a middle-aged supernova remnant, which GLAST will image.

Solar Physics

EGRET has detected gamma rays from a few solar flares, the best example of which was the one on June 11, 1991. For this flare, the photon energies extended into the GeV range, but no high-energy cutoff was detected. The emission lasted for hours after the impulsive phase of the flare, but the total duration was not constrained.

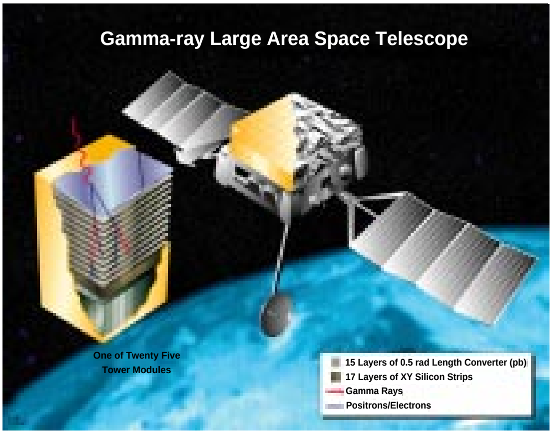
The two proposed explanations for the delayed gamma-ray emission are continuous acceleration and long-term plasma trapping, both of which involve exciting physics. Observations at the highest energies are vital for distinguishing these two hypotheses.



The extraordinary solar flare of June 11, 1991 was the best example observed by EGRET during the last solar maximum. GLAST will localize a bright flare like this to 2 arc minutes, which is much smaller than the 30-arc-minute diameter of the sun as seen from Earth.

GLAST will have the angular resolution to localize the emission sites on the sun, and the sensitivity to observe many flares up to 100 GeV over their entire durations to meaningfully address the problem of their nature. There are likely similarities between the particle acceleration processes in solar flares and in astrophysical jets, and therefore the insight we gain from studying the sun should be applicable to the much grander particle accelerators that we see elsewhere in the Universe.

GLAST Mission, Instrument and Technologies



A visualization of the GLAST spacecraft and one of its twenty five tower modules.

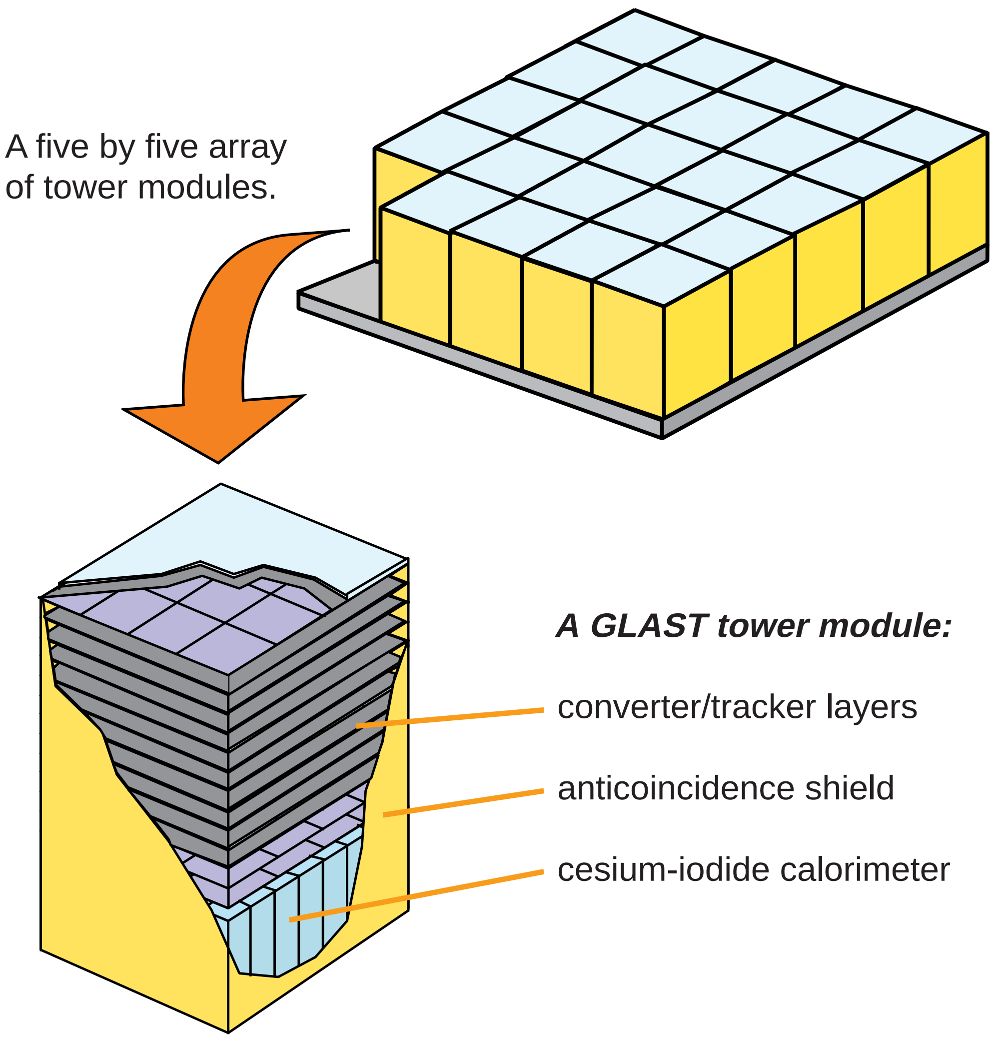
The primary instrument required for the GLAST mission is an imaging, wide field-of-view telescope that covers the energy range from 10 MeV to 300 GeV. Incident gamma rays are identified by recording the characteristic track signature that results from pair conversion in the presence of a nucleus. The telescope consists of many thin pair-producing heavy-metal foils interleaved with position-sensitive charged-particle detectors followed by an energy-measuring calorimeter. Measurement of the energy and direction of the electron-positron pair provide information about the energy and direction of the incident photon. Finally, the telescope requires an efficient anticoincidence system for rejecting the much larger charged-particle flux from cosmic rays and trapped particles, and an on-board trigger and data acquisition system. The major advances in particle physics detector technology in recent years have provided the major leap in observational capability necessary to achieve the desired scientific objectives within the cost of an intermediate-class (Delta II launch) mission.

GLAST has been selected as a NASA New Mission Concept in Astrophysics, and is summarized in the following table.

Primary instrument	imaging pair conversion telescope
Energy range	10 MeV to 300 GeV
Energy resolution	10%
Effective area	>8000 cm^2 (>1 GeV)
Single photon angular resolution[1]	<2.7°x(100 MeV/E)$^{0.9}$ (10 MeV to 1 GeV) <0.07° (>10 GeV)
Field of view[2]	>2.5 steradians
Point source sensitivity[3]	1 day: 3 x 10^{-7} photons cm^{-2} s^{-1} 1 year: 5 x 10^{-9} photons cm^{-2} s^{-1} 5 years: 2 x 10^{-9} photons cm^{-2} s^{-1}
Source location determination	30 arc seconds to 5 arc minutes
Mass	3000 kg
Power	650 W
Telemetry	300 kbps
Mission life	>2 years (planning for 5 years)
Orbit	low inclination ≤28.7°, 600 km
Spacecraft pointing	10 arc second knowledge; 2° accuracy
Operating modes	All-sky survey mode, and pointed mode (any direction at any time)

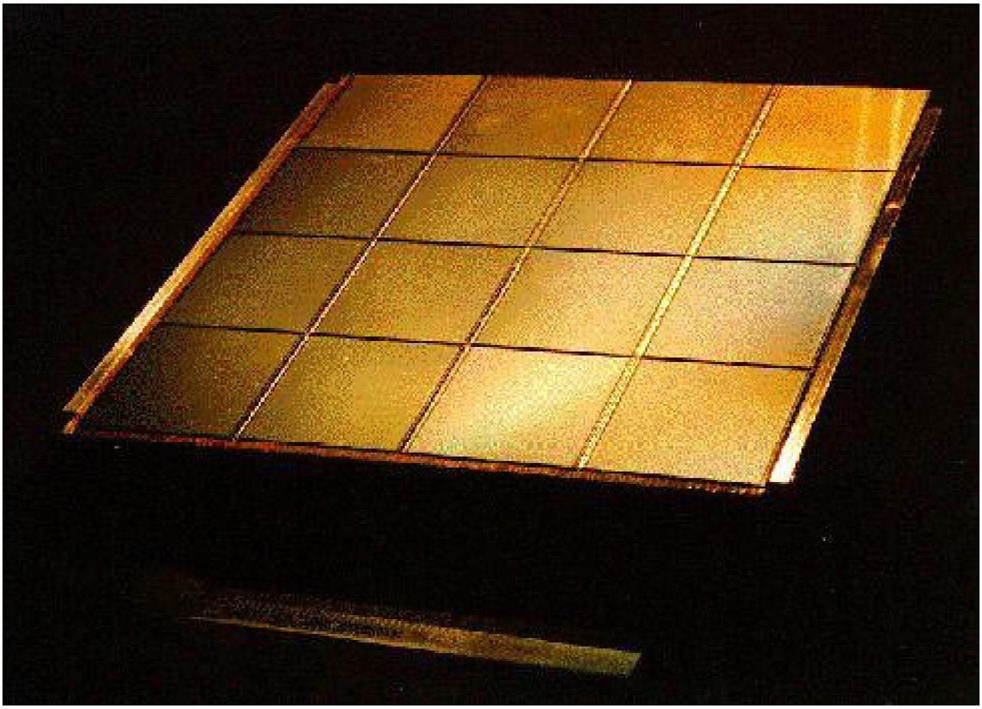
[1] 68% containment angle
[2] Full width at half maximum
[3] All-sky average, assumes scan-mode operation and high Galactic latitude

The GLAST instrument design is modular. The principal elements of the telescope are a segmented charged-particle anticoincidence shield, a gamma-ray converter/tracker, a calorimeter, and an on-board trigger and data acquisition system. Elements of all of these are present in each GLAST tower module. The modular design of GLAST has the advantages associated with redundancy and avoids the dead-time and data-rate problems associated with monolithic designs.



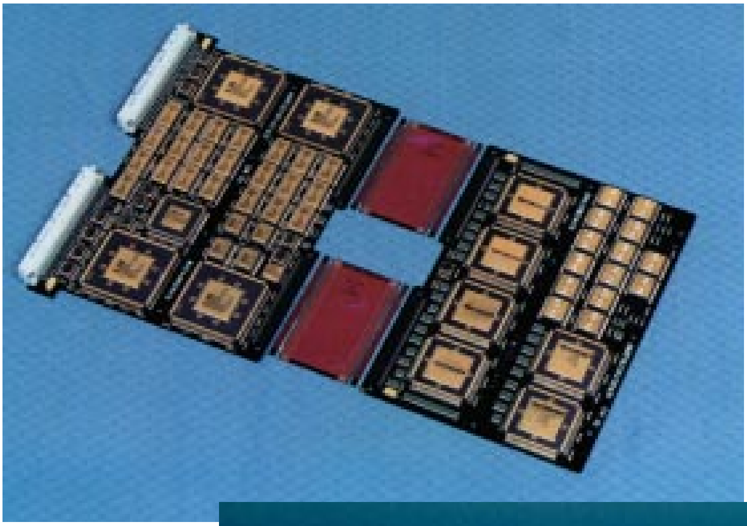
The major developments in using semiconductor devices for particle detection over the past decade are the main technical stimulus behind GLAST. In particular, large-area silicon-strip detectors have been developed for particle tracking in major high-energy particle-accelerator experiments. Much of this recent innovation was brought about because of the challenges that were presented by the Superconducting Super Collider.

Besides having to withstand the launch and space environment, the next-generation high-energy gamma-ray telescope must be capable of measuring a relatively low flux of high-energy celestial gamma rays in the presence of a much higher flux of high-energy cosmic rays, Earth-albedo gamma rays, charged particles trapped in Earth's magnetic field, and secondary charged particles.

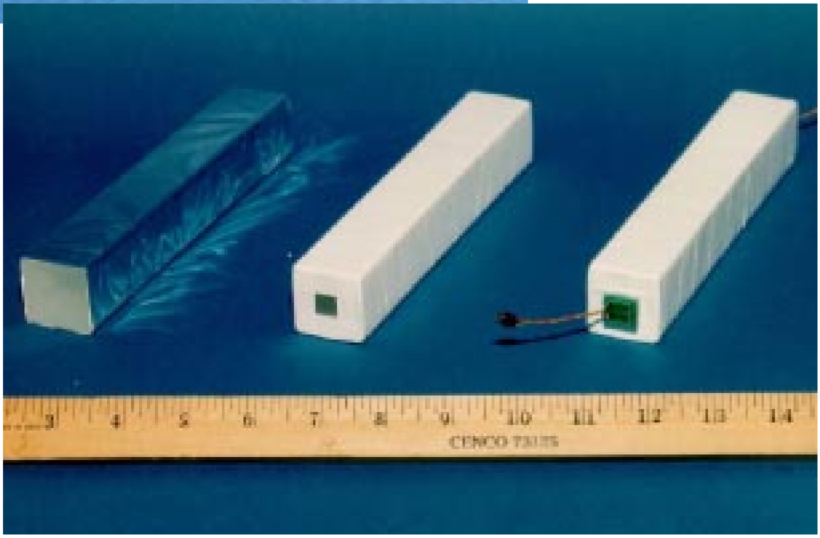


A silicon-strip detector tracker plane.

In particular, the particle background rejection required is driven by the expected level of the weakest gamma-ray signal, which is the diffuse isotropic (presumably extragalactic) gamma-ray background. Detailed Monte Carlo simulations show that GLAST can reach the goal of having residual background rates less than 1% of the diffuse isotropic gamma-ray flux.

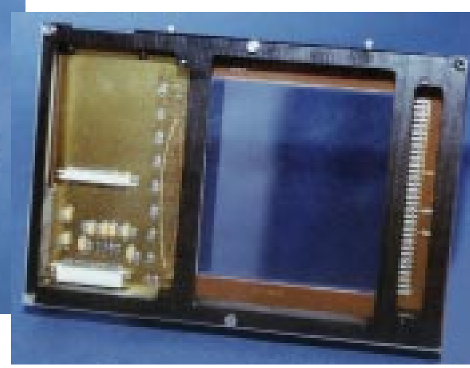


A 32-bit radiation-hard processor.



Cesium-iodide calorimeter elements.

In the baseline GLAST design, each plane of the converter/tracker has two sets of strip detectors that can accurately measure charged-particle tracks in two orthogonal dimensions. These tracks can be used to identify gamma-ray interactions, since the showers resulting from gamma-ray conversions have different properties than those caused by high-energy hadrons (i.e., protons, neutrons, etc...). By observing the pattern of charged particle "hits" in the silicon-strip tracker and the energy deposition pattern in the calorimeter, events caused by gamma rays that enter the front of the instrument can be distinguished from the much higher fluxes of cosmic rays and trapped radiation incident on the instrument. Also, Earth-albedo gamma rays are easily identified and eliminated by their directional signature.

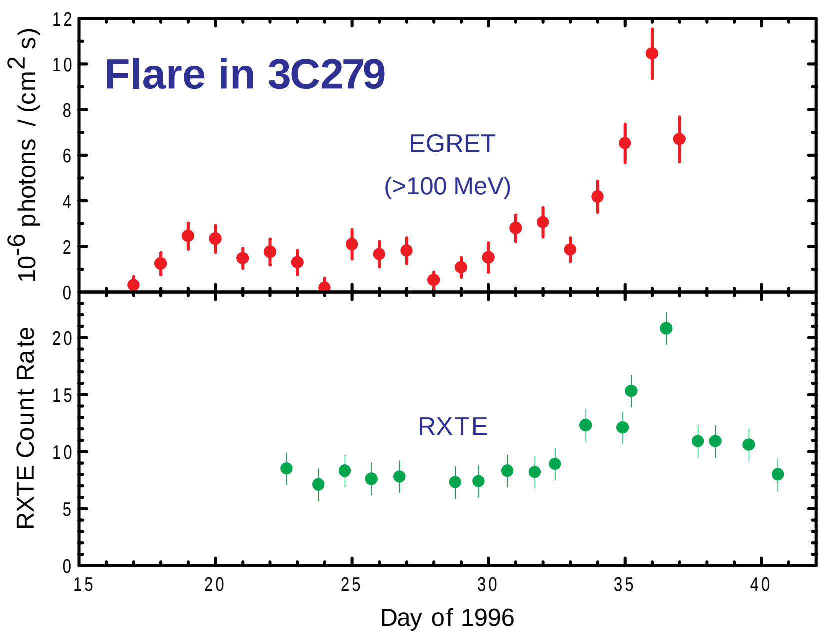



Gas microstructure detectors.

Several alternative detector technologies are being studied for possible use on the GLAST mission. Like silicon-strip detectors, these alternate technologies have also been developed for use in large particle-accelerator experiments. For the critical particle tracking aspect of a future mission, scintillating optical fibers and gas microstructure devices have shown some promise for increased performance (either higher telescope detection efficiency or better angular resolution). These new technologies also offer the prospect of lower cost. Laboratory tests and simulations of these detector technologies are in progress at several universities and government laboratories to determine their possible applicability to GLAST.

Guest Investigator Program and Public Outreach

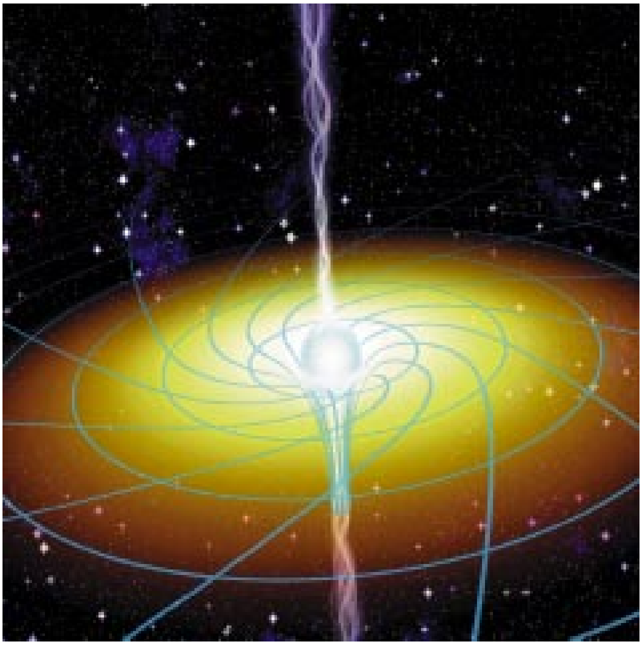
GLAST is envisioned as a facility for use by the astronomical community. A strong guest investigator program will be an integral part of the mission. The GLAST field of view will cover 20% of the sky with a much greater sensitivity than EGRET. From estimates based on the luminosity functions measured by EGRET, as many as several hundred sources will be detected by a single pointed observation of GLAST, and thus will attract the attention of a wide range of observers with a variety of specialties.



Multiwavelength observations of AGN flares are essential for understanding their nature (RXTE is the Rossi X-ray Timing Explorer).

Guest investigations are needed not only to study the multitude of gamma-ray detections, but also to make multiwavelength observations. The production and annihilation of the highest energy photons require the presence of lower energy photons. Only simultaneous measurements at all wavelengths will ascertain the complete picture of these complex processes.

GLAST observations of extremely energetic and dynamic phenomena will intrigue the general public. Flares from distant blazars, powerful lighthouse beams from pulsars, and the mysterious gamma-ray bursts are all fascinating topics that capture the imagination. GLAST's discoveries will be disseminated via public lectures, press releases, articles in the popular media, and the Web. Additional outreach programs, such as planetarium shows, science museum exhibits, and instructional materials for K-12 teachers (with lesson outlines and demonstrations), are planned.



Frame dragging around a rotating black hole (courtesy of Joe Bergeron and Sky & Telescope).

Glossary

Accretion — the process whereby matter from a normal star or diffuse cloud is captured by a compact object such as a black hole or neutron star.

Active Galactic Nuclei (AGN) — the central regions of some galaxies that appear as point-like sources of radiation. Believed to be supermassive black holes accreting nearby matter.

Anticoincidence system — a system on a gamma-ray telescope that triggers when it detects an incoming charged particle so that the telescope will not mistake the particle for a gamma ray.

Black hole — any object with gravity so strong that not even light can escape.

Blazar — a type of AGN that often appears as a point-like source of bright, highly variable radiation.

Boson — a subatomic particle with integer spin, such as a photon, a pion and certain atomic nuclei.

Calorimeter — a heavy object with a component that scintillates when electrons or positrons pass through, used to measure a gamma ray's energy.

Converter — a dense material, such as lead or tungsten, used to convert a gamma ray into an electron-positron pair.

Cosmic rays — relativistic elementary particles, such as electrons, protons or atomic nuclei, that exist throughout interstellar space.

Cosmology — the study of the origin, structure and evolution of the Universe.

Dark matter — a non-luminous gravitational component of the Universe invoked to explain the internal motions of galaxies and the motions of galaxies within clusters of galaxies.

Diffuse Galactic emission — non-point-source gamma-ray emission from the plane of the Galaxy. Mostly due to interactions of cosmic rays with interstellar material.

Diffuse isotropic emission — non-point-source gamma-ray emission that is uniform across the sky. Believed to be the emission from a multitude of unresolved AGN.

EGRET — Energetic Gamma Ray Experiment Telescope on board the Compton Gamma Ray Observatory (operates from 30 MeV to 30 GeV).

Electron volt — a unit of energy, sufficient to excite atoms to emit visible light (keV = 1000 eV, MeV = 1000 keV, GeV = 1000 MeV).

Flux — a detector-independent measure of the brightness of a gamma-ray source.

Gamma ray — a photon more energetic than an X-ray (more than about 50,000 electron volts).

Gamma-ray burst — brief intense random gamma-ray emission from an unknown source.

GLAST — Gamma-ray Large Area Space Telescope (to operate from 10 MeV to 300 Gev).

Inverse Compton scattering — a collision between a photon and an energetic electron that transfers energy from the electron to the photon.

Jet — a collimated stream of relativistic particles which flows from a central source.

Light year — the distance travelled by light in one year (6×10^{12} miles).

Lorentz factor — $\gamma = 1/[1 - (v/c)^2]^{1/2}$, where v is the speed of an object, and c is the speed of light.

Neutrino — a stable elementary particle with no charge, almost zero rest mass, and a spin of 1/2.

Neutron star — a compact star with a radius of about 10 km and a mass of about 1.4 solar masses that internally supports itself against gravity by the strong nuclear force between neutrons.

Pair annihilation — an interaction between a particle and its antiparticle that results in the destruction of the pair of particles and the emission of a pair of gamma rays.

Pair production — the inverse process to pair annihilation where a particle-antiparticle pair are created from a pair of photons, including when a gamma ray passes close to an atomic nucleus.

Parsec — a historical unit of distance equal to 3.26 light years. A gigaparsec is 10^9 parsecs.

Pion — an unstable nuclear particle with a rest mass between that of an electron and a proton. Also known as the π meson.

Photon — the fundamental particle of light. The energy of a photon is proportional to its frequency.

Pulsar — a type of neutron star with a beam of emission that sweeps around as the star rotates.

Positron —the antiparticle of the electron. Capable of mutually annihilating with an electron.

Redshift — the shift of spectral lines to longer wavelengths either due to the motion of the source away from the observer or very strong gravity.

Relativtistic — approaching the speed of light.

Scintillation — the emission of light that occurs when electrons or positrons excite a substance in a transparent material they are passing through.

Solar flare — a burst-like emission of radiation from disturbances in the sun's outer atmosphere.

Spectrum — the number of photons a source emits as a function of energy.

Strong nuclear force — a short range nuclear force that operates within an atomic nucleus.

Supernova — a violent explosion that is the endpoint of the evolution of a massive star. Often a compact object is produced such as a neutron star or black hole.

Supernova remnant — the expanding gaseous shell ejected by a supernova explosion.

Synchrotron emission — electromagnetic radiation emitted by charged particles when accelerated by a magnetic field.

Tracker — part of a high-energy gamma-ray telescope used in tracking the trajectories of the electron-positron pairs produced by the converter.

Weak force — a short range nuclear force responsible for radioactivity and the decay of certain atomic nuclei.

WIMP — a very weakly interacting relatively massive elementary particle, such as a neutralino.